Forward Global Calibration of Wide-Field Optical Surveys

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“The Last Kiloparsec”

UC Davis

December 14, 2015

Flux, Magnitude, and Passbands

Observational Quantities

Flux of photons observed through the atmosphere with the telescope and camera in a specific direction and time … the *observational passband*

DES and LSST surveys will generate hundreds to thousands of these for every celestial object in the footprint – billions in total

Not practical to do science with observational magnitudes

Standard Quantities

A set of (in principle arbitrary) reference passbands used to state the results of observations of celestial objects

Must acquire sufficient information about the *observational passband for each exposure* to convert observed flux to magnitudes that would be seen through the corresponding *standard passband*

All photometric specifications apply to *standard fluxes and magnitudes*

Photometric SRD Specifications

Specifications for isolated bright stars (17 < r < 20)

- Will address the first two requirements in today’s talk ... these can be characterized as requirements on calibration *precision* …

    - Repeatability of measured flux no worse than 0.005 mag (rms)

    - Uniformity of internal scale across the sky 0.010 mag (rms) in *g,r,i,z* ; 0.020 in other bands

- Two additional specifications not addressed here are requirements on calibration *accuracy* … methods to achieve them largely rely on identification and use of “standard celestial sources” …

    - Transformations between internal photometric bands known to 0.005 mag (rms) in *g,r,i,z*;   0.010 to other bands

    - Transformation to a physical scale with accuracy of 0.020 mag

Forward Global Calibration (FGC) Concept

➢ Incorporate into a "forward" photometric analysis:

- In-situ measurements of instrumental response

- Independent measurement of atmospheric constituents cotemporaneous with survey observations

Stubbs & Tonry, ApJ 646, 1436 (2006)

- Extensive computational modeling of atmospheric properties from climate science

Burke, et al., ApJ. 720, 811 (2010)

➢ Global fit to broadband survey imaging and supporting auxiliary data to extract parameters that define underlying atmospheric and instrumental transport and response … not zero-points of individual observations

➢ *Compute* observational passband for every exposure

Why FGC?

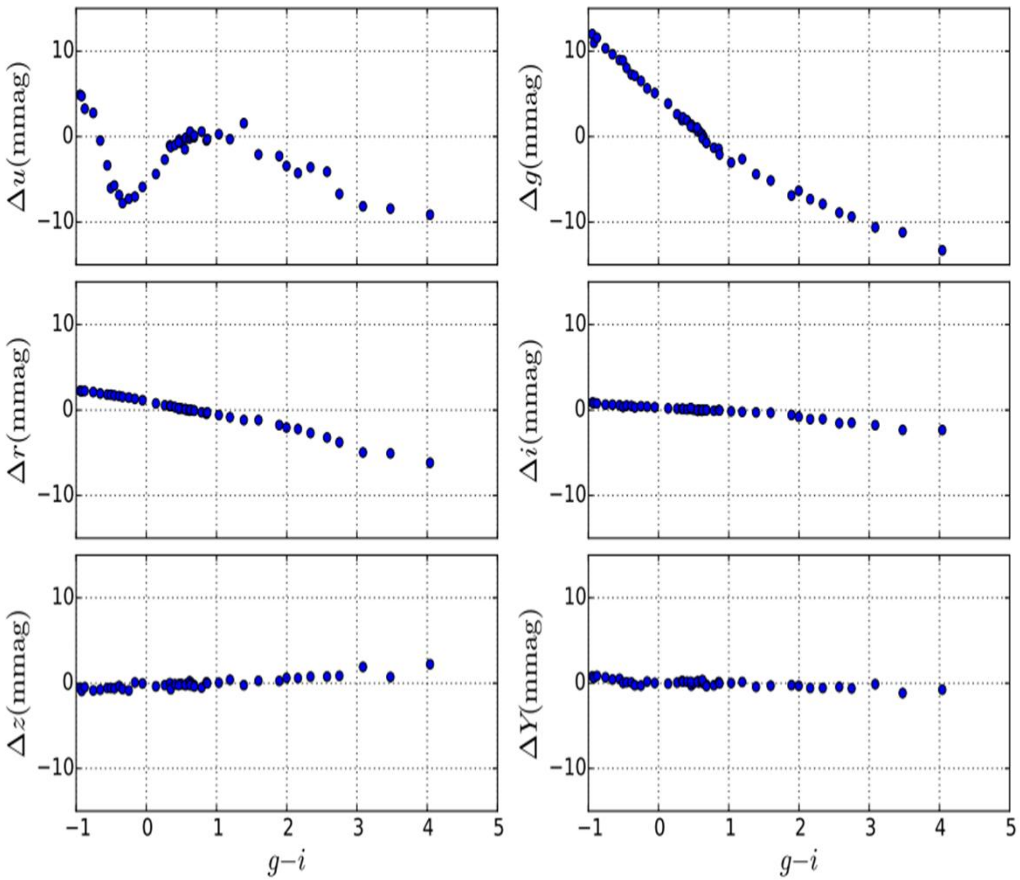
- Calibrate many observations with relatively few parameters that fully describe underlying observing conditions
- Freedom to choose observations that best determine conditions
- Exposures taken in any band contribute to calibration of all bands
- Naturally incorporates data from auxiliary instrumentation – DECal, aTmCam, SkyCams, and data from CTIO operations and environment
- Corrects (to first-order) chromatic dependence on SEDs of the sources used for calibration, and application of calibration to sources with differing SEDs …

… both necessary to meet DES and LSST specifications

… leads to a new paradigm for photometric calibration

Standard and Observational Magnitudes
Dependence on Source SED

DARK ENERGY SURVEY



Residual errors in magnitudes of stars observed at airmass 1.8 and corrected to standard airmass 1.2 using error-free “flat SED” calibration

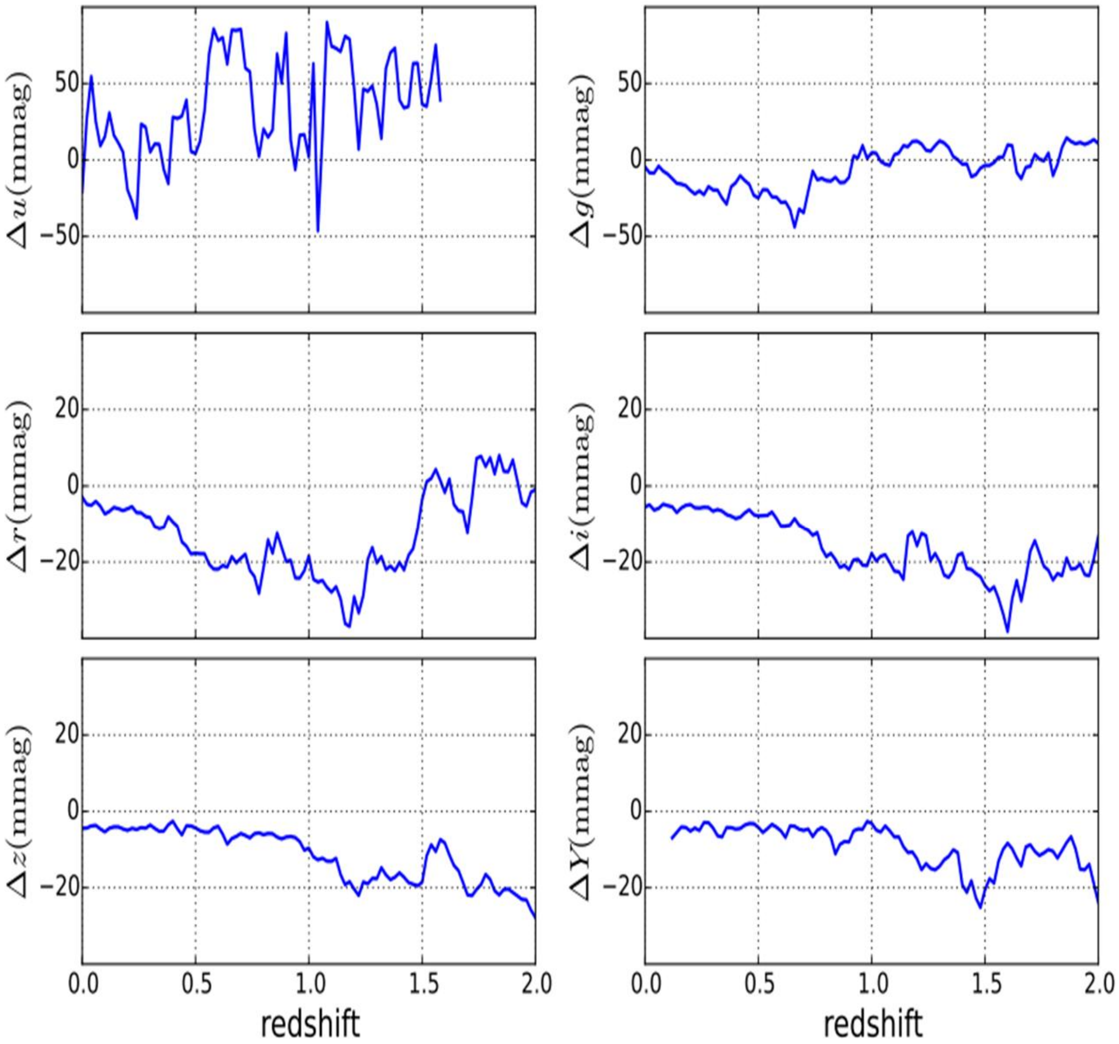
$\rightarrow$ color-dependent errors up to 10-15 mmag in g and r bands

Simulations by T. Li, DES publication in preparation (2015)

See also L. Jones, et al. LSST-doc (20xx)

Standard and Observational Magnitudes
Dependence on Source SED

DARK ENERGY SURVEY



Residual errors in magnitudes of elliptical galaxies at $0 < z < 2$ observed at airmass1.8 and corrected to standard airmass1.2

$\rightarrow$ redshift-dependent errors up to 20-30 mmag in grizY bands

Forward Global Calibration
with First-order Chromatic Corrections

The number of ADU counts assigned to a celestial source viewed through an observational passband

$$S_b(x, y, \mathrm{alt}, \mathrm{az}, t, \lambda) = S_b^{\mathrm{inst}}(x, y, t, \lambda) \times S^{\mathrm{atm}}(\mathrm{alt}, \mathrm{az}, t, \lambda)$$

for telescope aperture A and exposure time ΔT is written

$$\mathrm{ADU}_b^{\mathrm{meas}} = A \int_0^{\Delta T} dt \int_0^{\infty} F_\nu(\lambda) S_b(x, y, \mathrm{alt}, \mathrm{az}, t, \lambda) \lambda^{-1} d\lambda$$

where,

$F_\nu(\lambda)$ is the celestial source SED at the top of the atmosphere defined as in SDSS (Fukugita et al., 1996) with units ergs/cm^2/sec/Hz

The integration increment $d\lambda/\lambda$ converts ergs to photons.

First-Order Chromatic Expansion

DARK ENERGY SURVEY

Make first-order linear approximation $F_\nu(\lambda) = F_\nu(\lambda_b) + F'_\nu(\lambda_b)\,(\lambda - \lambda_b)$

where λ_b is chosen, for example, as the photon-weighted average wavelength of the passband.

Then, $\quad ADU \propto F_\nu(\lambda_b) \int S_b(\lambda)\, d\lambda/\lambda \quad + \quad F'_\nu(\lambda_b) \int S_b(\lambda)\,(\lambda - \lambda_b)\, d\lambda/\lambda$

Define, $\quad I_0(b) \equiv \int S_b(\lambda)\, d\lambda/\lambda$, and $\quad I_1(b) \equiv \int S_b(\lambda)\,(\lambda - \lambda_b)\, d\lambda/\lambda$

so that, $\quad ADU \propto F_\nu(\lambda_b) \times [I_0(b) + I_1(b) \times F'_\nu(\lambda_b)/ F_\nu(\lambda_b)\,]$

The two intergrals I_0^{obs} and I_1^{obs} are the data products from the calibration.

Transformation from an observed passband to the corresponding standard passband can be shown to be (e.g. LSST Science Book),

$$mag\_toa^{std} = mag^{obs} + 2.5 \log_{10}[\, I_0^{obs}\,]$$

$$+ 2.5 \log_{10}[\, [1+(F'\nu/F\nu) \times (I_1^{obs}/I_0^{obs})] \,/\, [1+(F'\nu/F\nu) \times (\, I_1^{std}/I_0^{std}\,)]\,]$$

Exposure-by-Exposure Chromatic Calibration
A Research Project

Determine mag_toa^{std} , $F_\nu(\lambda_b)$, and $F'_\nu(\lambda_b)$ for all stars on a given exposure from magnitudes calibrated by a previous iteration of calibration fit.

Use uncalibrated instrumental magnitude for each star and define

$$\Delta m^{obs} \equiv mag^{obs} - mag\_toa^{std}(star)$$

Same math that yields conversion to standard passband gives,

$$proxy(obs) \equiv 10 ** (-0.4 \; \Delta m^{obs})$$

$$= I_0^{std} \times [\, I_0^{obs} + I_1^{obs} \times F'_\nu(\lambda_b) / F_\nu(\lambda_b) \,] \,/\, [\, I_0^{std} + I_1^{std} \times F'_\nu(\lambda_b) / F_\nu(\lambda_b) \,]$$

Linear equation in I_0^{obs} and I_1^{obs}. So minimize over stars with range of colors on each exposure,

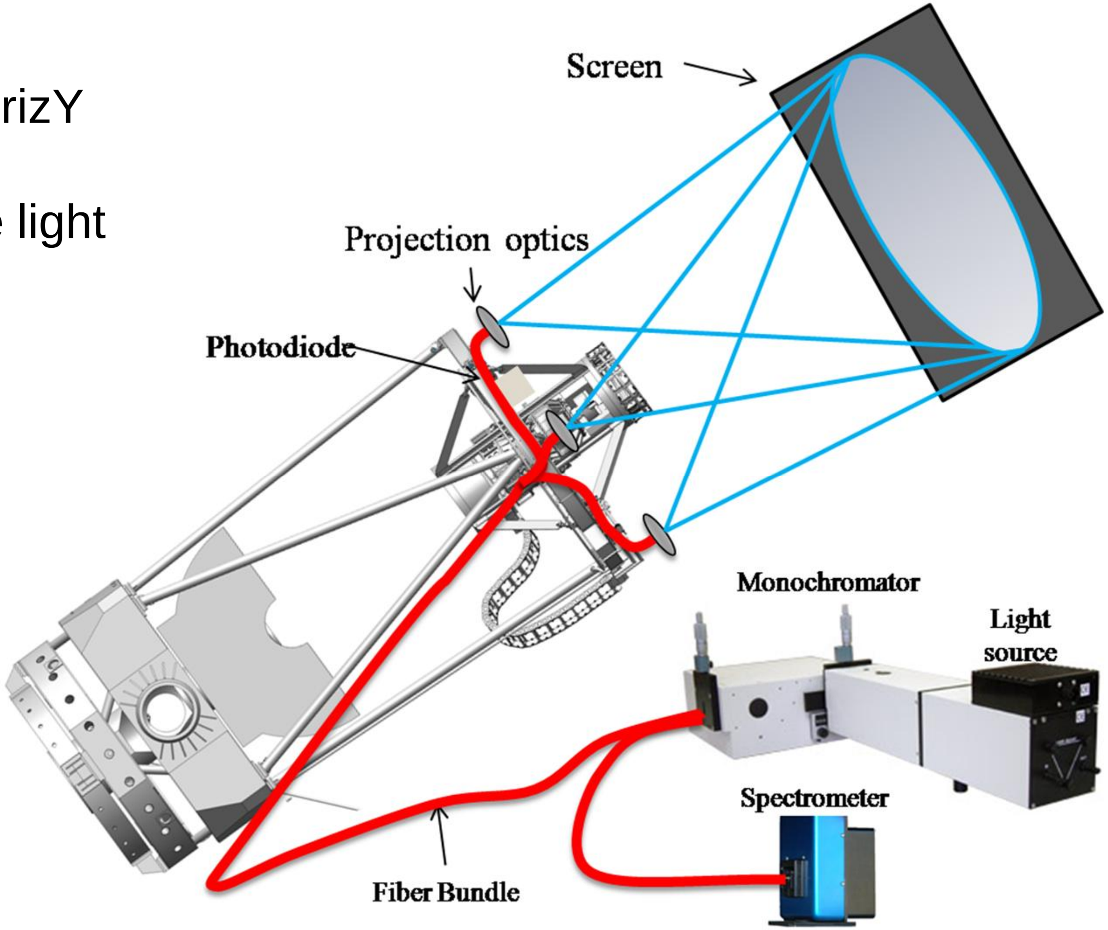
$$X^2 = \Sigma \; (\, proxy(obs) - RHS(I_0^{obs} , I_1^{obs}) \,)^2 \; / \, \sigma_{proxy}^2$$

to retrieve the integrals of interest. This completes a calibration of this exposure!!

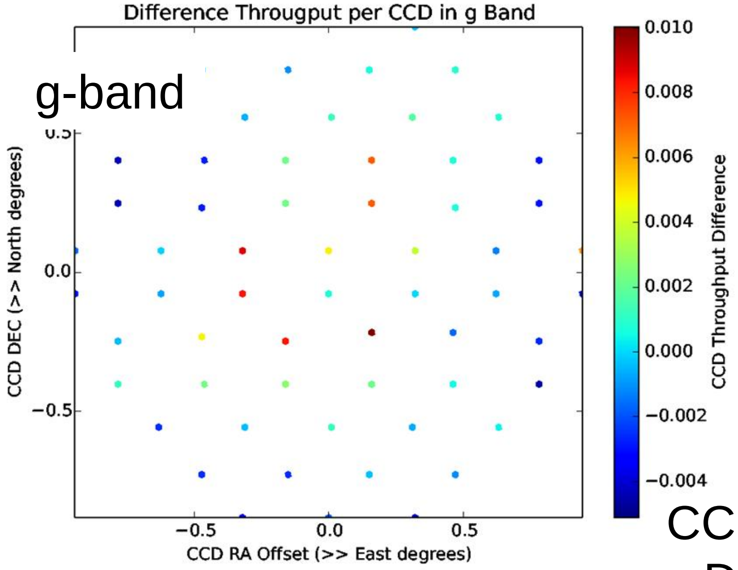
DES DECal Instrument Calibration System

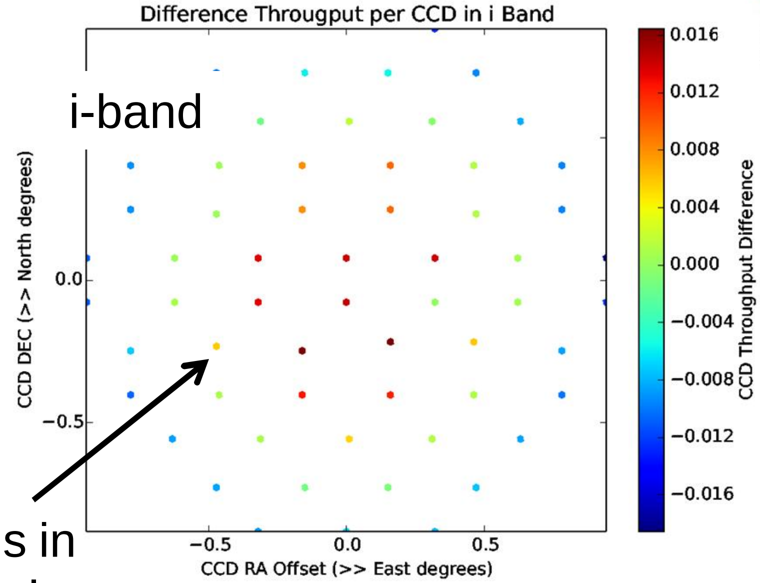
In-dome projection system with monochromatic and white light options

Monochromatic scans of grizY bands taken 2-3 times per observing season … white light flats taken nightly

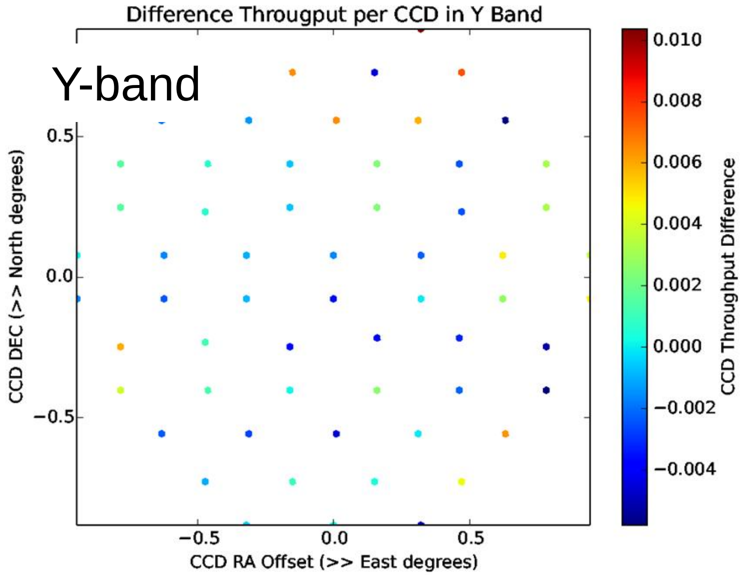


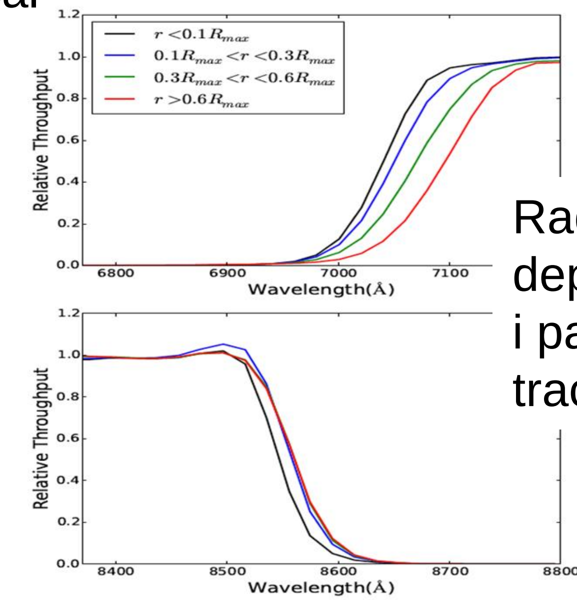
Uniformity of Instrument Response





CCD locations in DECam focal plane





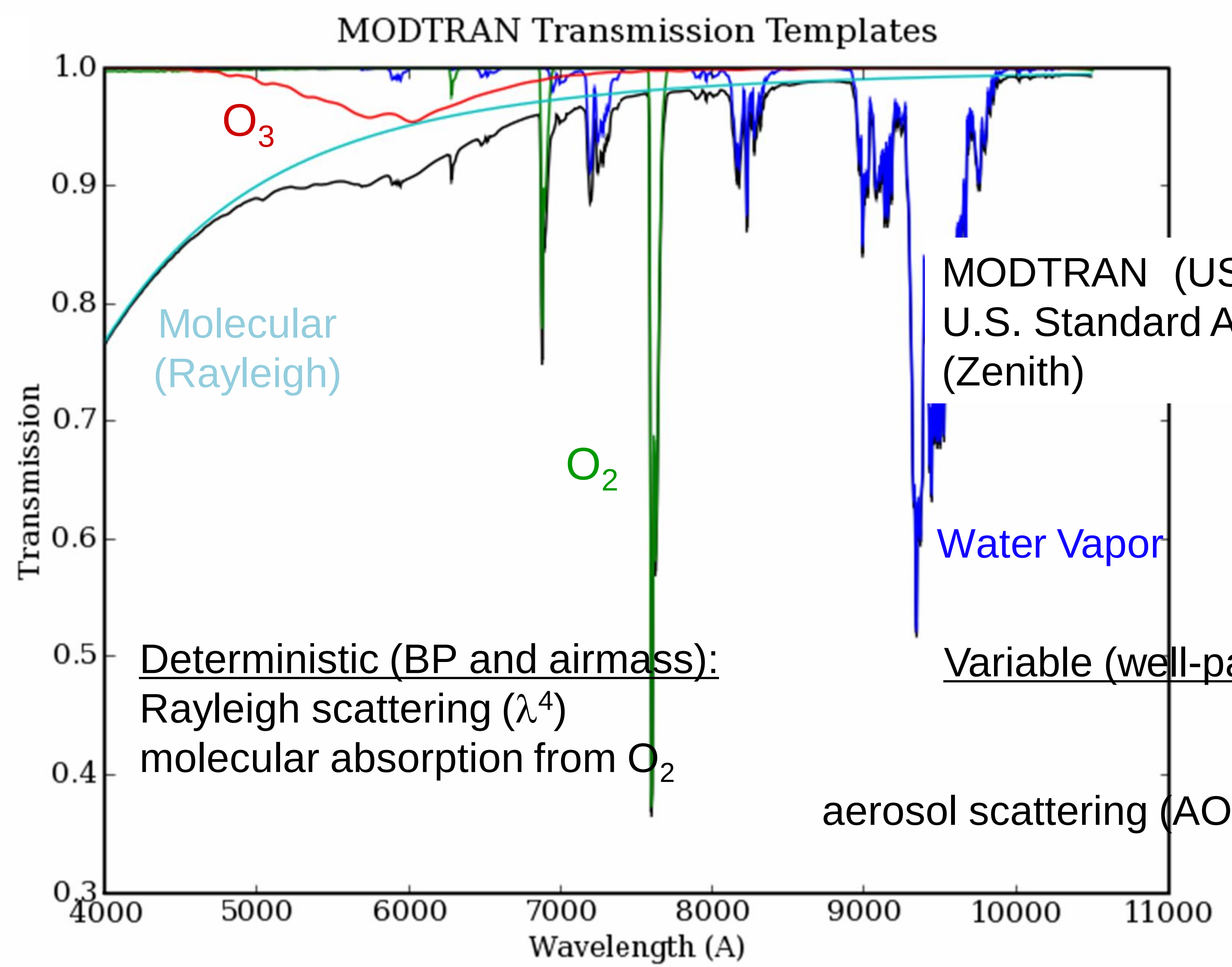
Radial dependence of i passband traced to filter

→ difference from average (standard) response included in I_1 integrals

Atmospheric Models and Calculations

DARK ENERGY SURVEY

Large Synoptic Survey Telescope



MODTRAN (USAF)
U.S. Standard Atmosphere (1976)
(Zenith)

<u>Deterministic (BP and airmass):</u>

Rayleigh scattering (λ^4)

molecular absorption from O_2

<u>Variable (well-parameterized):</u>

ozone O_3

water vapor

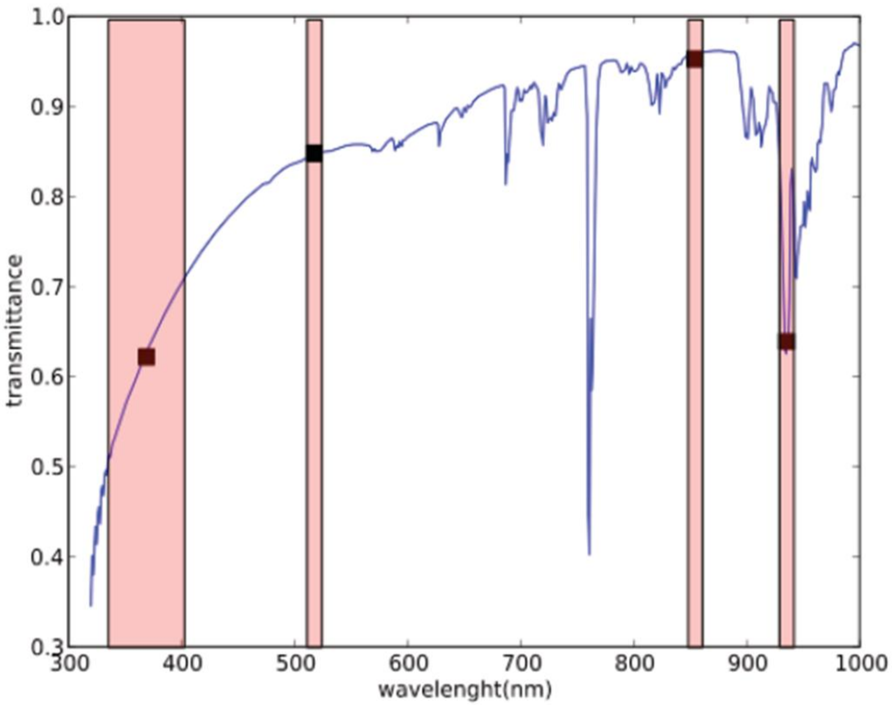
aerosol scattering (AOD(550nm), λ^α)

clouds (gray)

aTmCam

atmospheric Transmission monitoring Camera

Li, T., et al., SPIE, (2014)



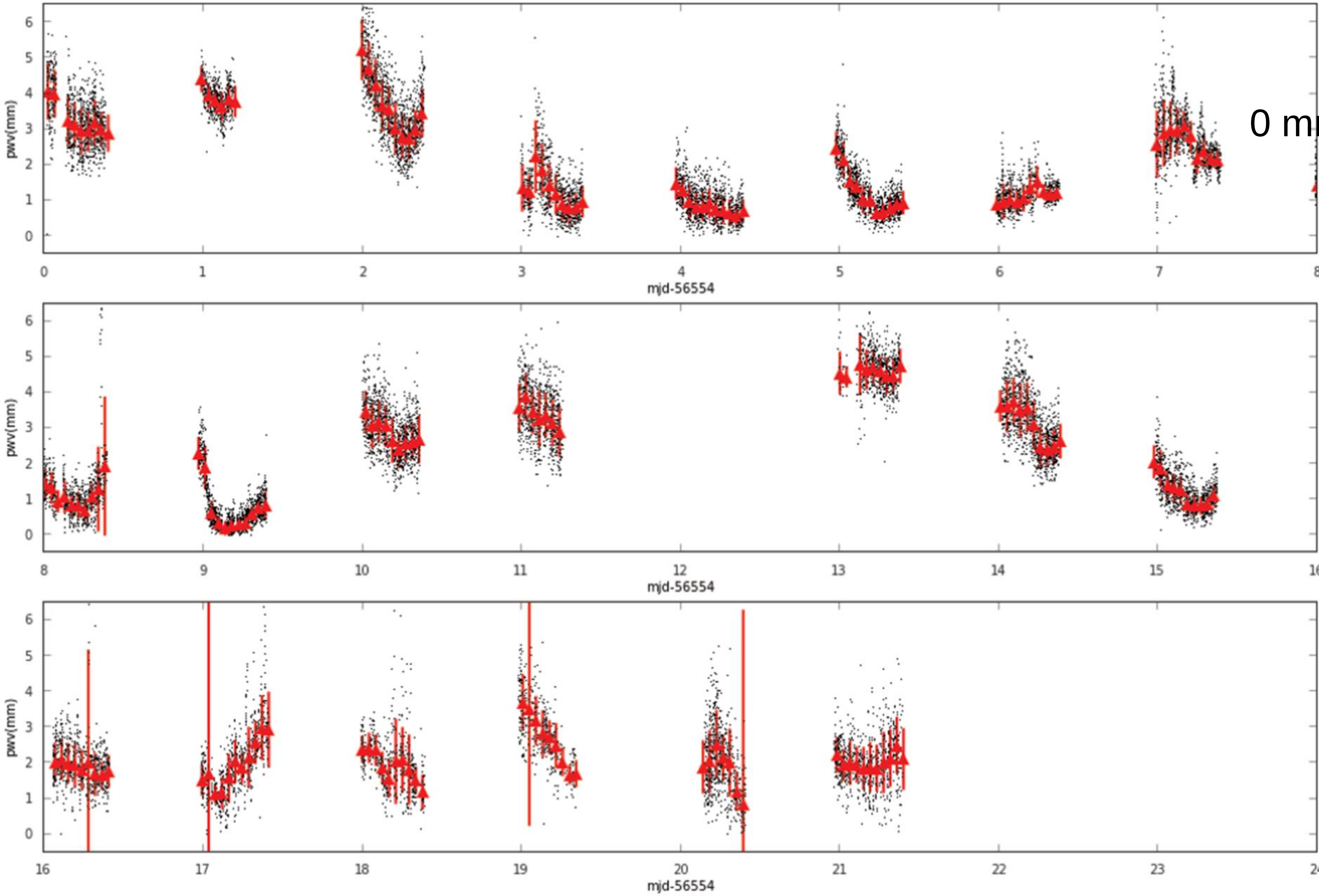
Prototype observing in Fall 2013 during DES SV period

Production camera installed a producing data Fall 2015 for DES Year 2

Precipital Water Vapor

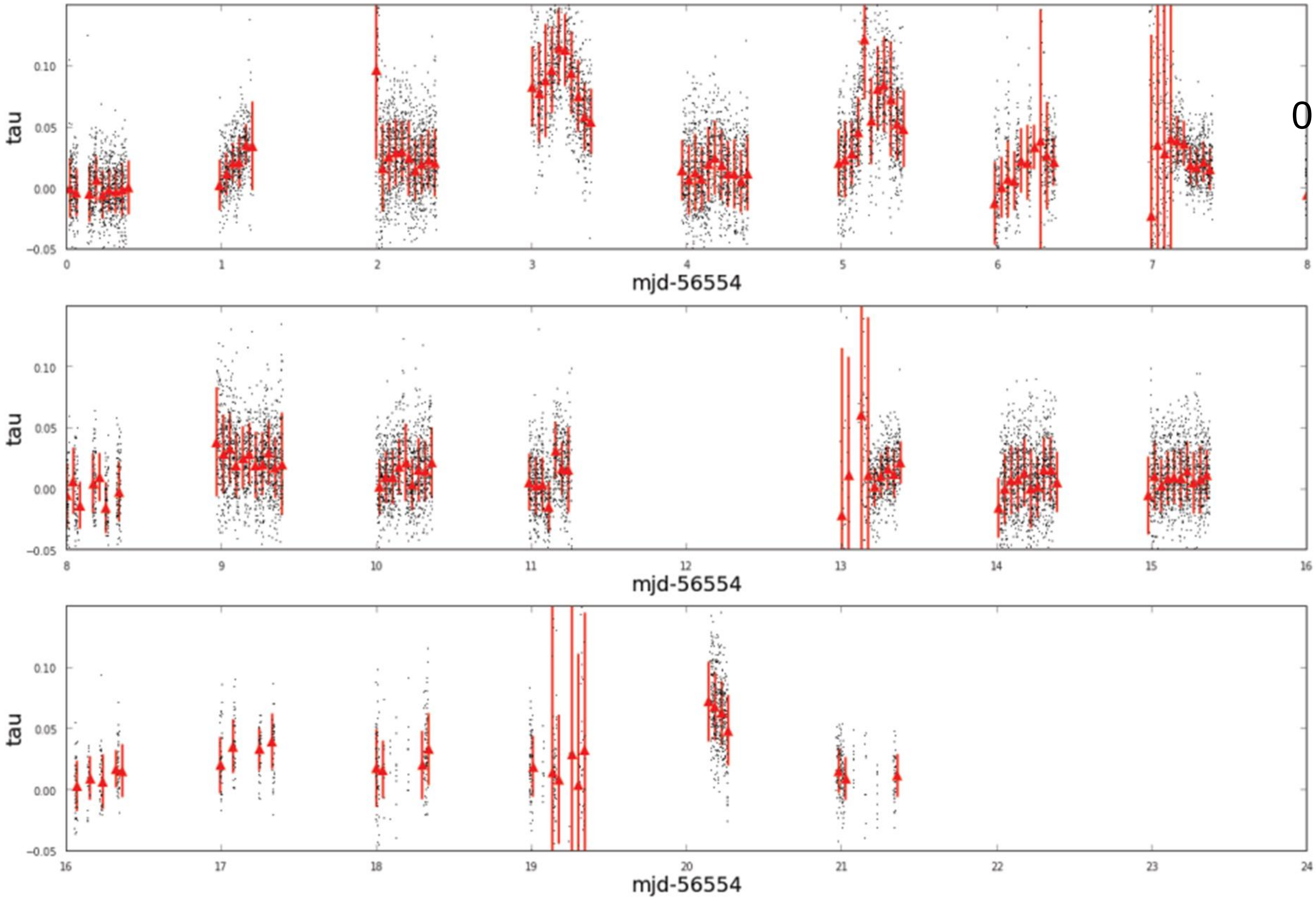
aTmCam 21 nights Sept-Oct 2013

DARK ENERGY SURVEY



0 mm – 6 mm

Aerosol AOD (550nm)
aTmCam 21 nights Sept-Oct 2013

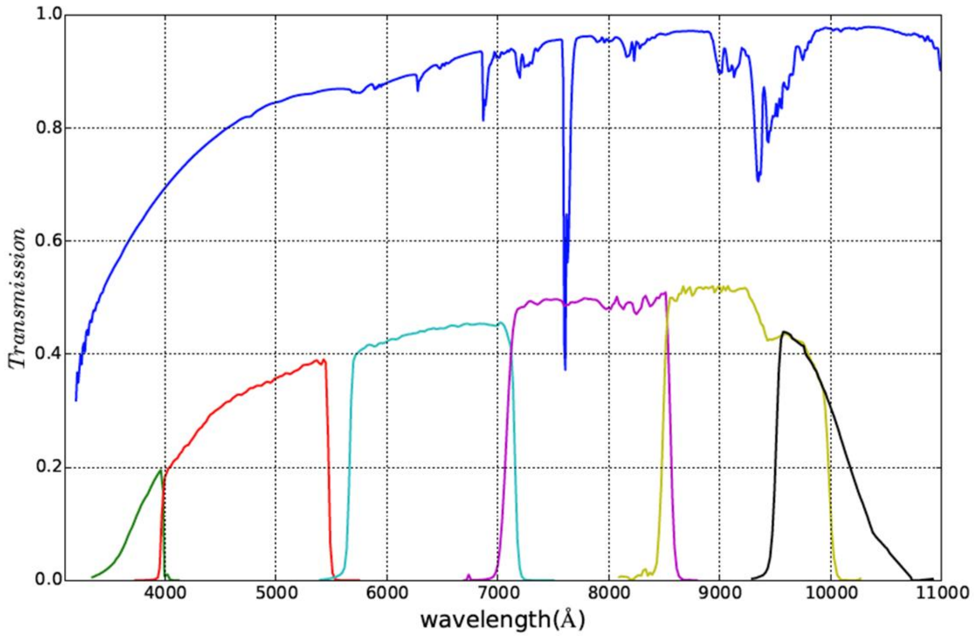


0 – 0.15

Standard Passbands

Choose set of standard passbands to be close to the most common observational passbands encountered in the survey

This will minimize error introduced by the approximations that are necessary to convert from observational to standard values



Atmospheric constituents from historical data and DES SV data …

Component	Standard
Pressure	$P_0 = 779$ hpa
Aerosol	$\mathrm{AOD}_{550} = 0.02,\ \alpha = 1$
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PWV	$\mathrm{PWV} = 3$ mm
Ozone	$\mathrm{Ozone} = 270$ DU
Airmass	$X = 1.2$

Instrumental throughput and detection defined by average over the entire focal plane (Sept 2013 DECal scans)

Forward Global Calibration Module (FGCM)

DARK ENERGY SURVEY

Step 0   Acquire and synchronize auxiliary measurements

- Instrumental parameters
  - Camera CCD compliment
  - Telescope mirror surface maintenance
  - Periodic DECal scans
- Atmospheric parameters
  - Barometric pressure
  - aTmCam data (Year 2 onward)

Step 1 Build a catalog of 10 million standard stars to span the DES footprint

- Identify "photometric" exposures and nights (or sections of nights)
- Identify standard stars seen minimal times in "photometric" conditions

Step 2 The FGCM fit

Find instrumental and atmospheric parameters that minimize dispersion of repeated "photometric" measurements of the standard magnitudes of internal standard stars $\rightarrow$ yields standard magnitudes for standard stars

Step 3 Final Calibration

Use fitted parameters and standard magnitudes to *compute* I_0 and I_1 parameters for individual CCD images (60-61 per exposure in Year 1)

Calibration of DES Year 1 Data (no aTmCam)

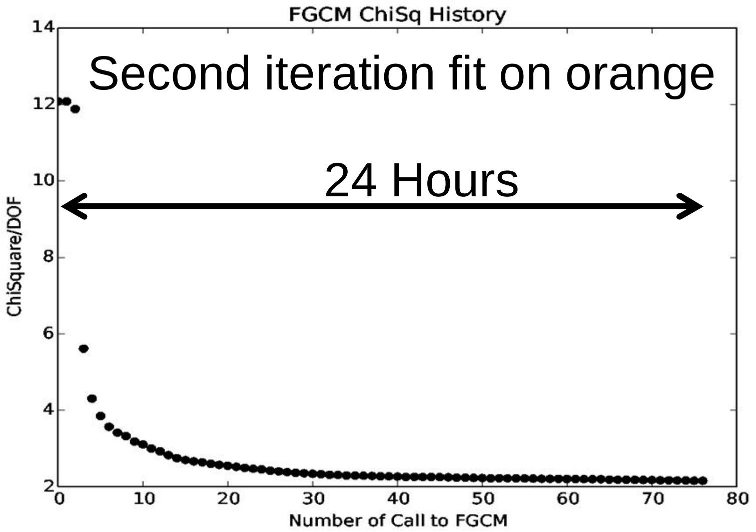
DARK ENERGY SURVEY

- Approx 2000 sq degrees targeted nominally 4 times in grizY
  - gr on dark nights
  - iz on bright nights
  - Y on bad bright nights (ok, so Y isn't that popular yet)
- 12 "Supernova" fields repeatedly targeted (preferentially poor seeing nights)
  - grizz in a sequence – strong constraint on instrument throughput

FGCM Fit

- 3,800,000 internal standard stars
- 15,800 exposures
- 102/123 nights wholly or partially photometric enough to get a fit included 95% of exposures taken

$\rightarrow$ 824 parameter fit to 47,644,216 DOF



FGCM Final Calibration

$\rightarrow$ Computed 934,000 I0 and I1 calibration parameters for 958,000 CCD images (97.3% success rate)

Maintenance of Telescope and Camera Optics
(Blanco + DECam)

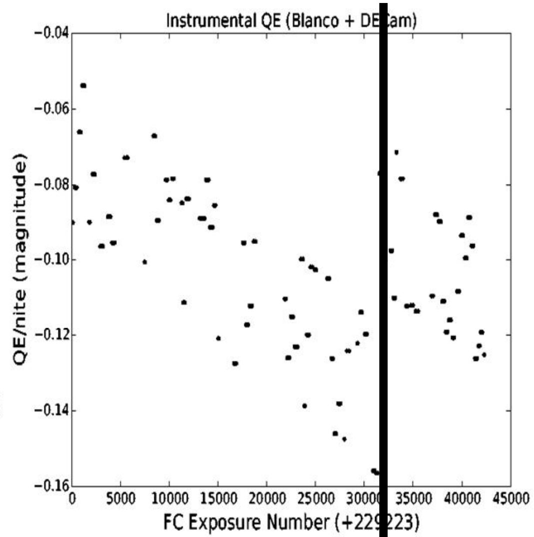
DARK ENERGY SURVEY

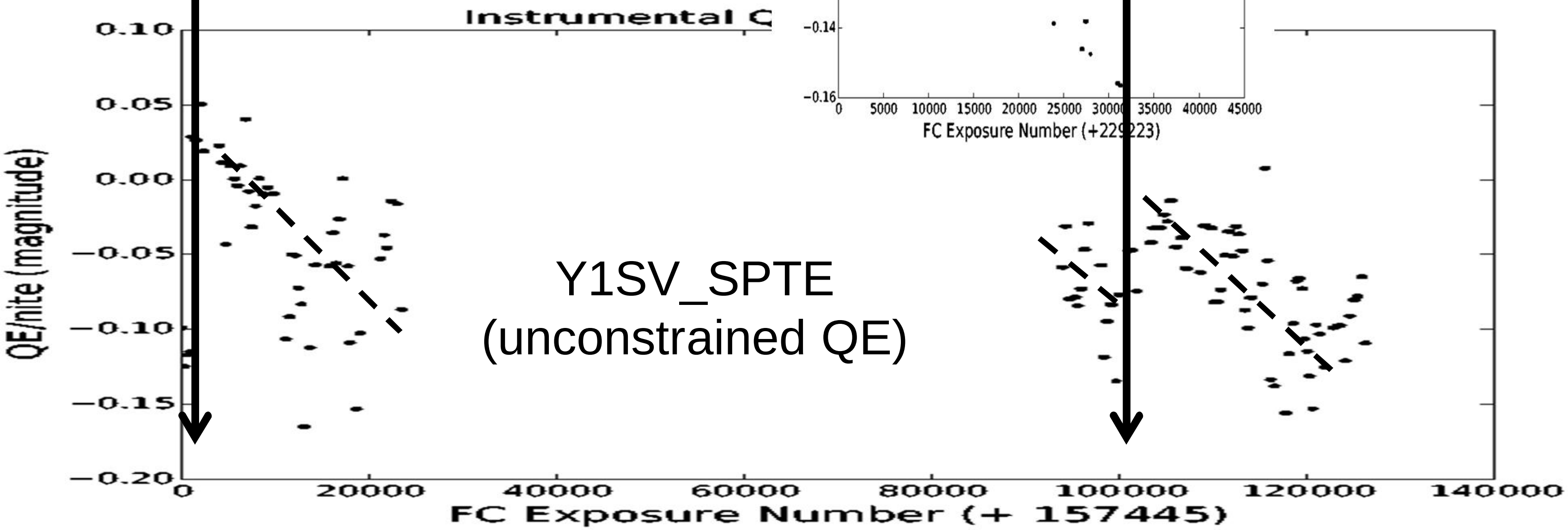
Find that loss of throughput is nearly a constant 0.0007/day

Mirror Wash
December 6, 2012

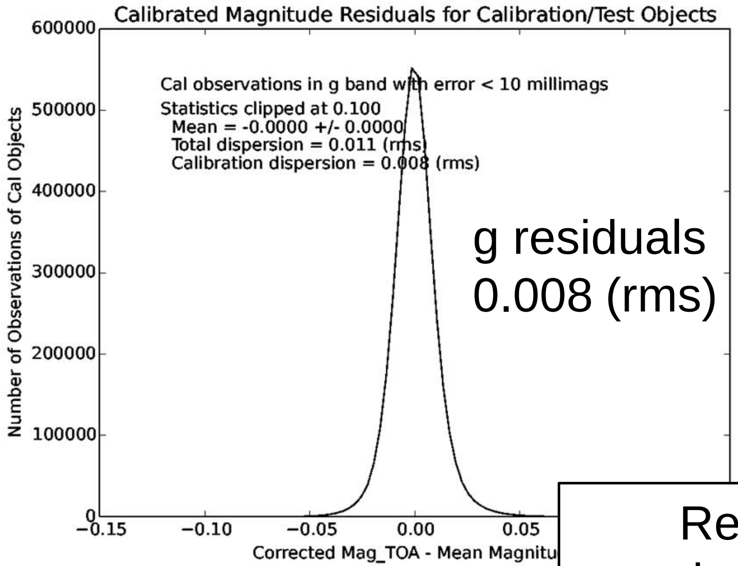
Mirror Wash
December 5, 2013

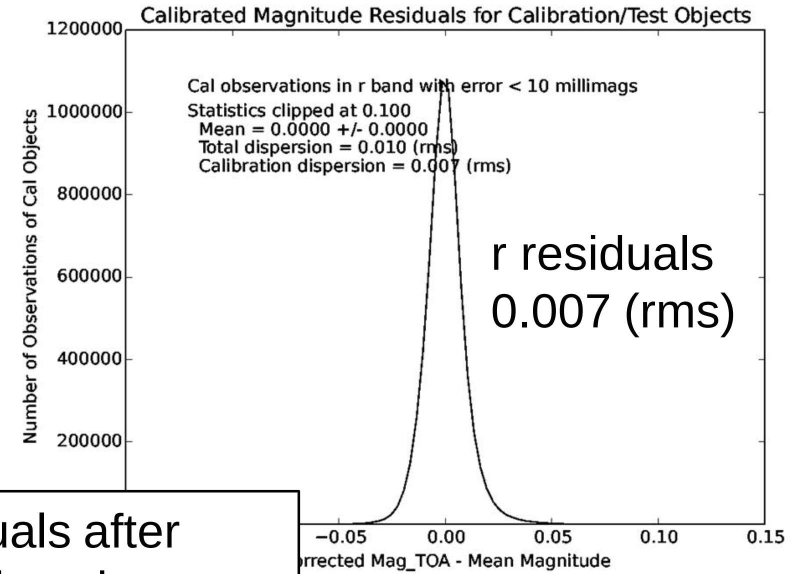
Y1A1_WEST
(constrained QE)



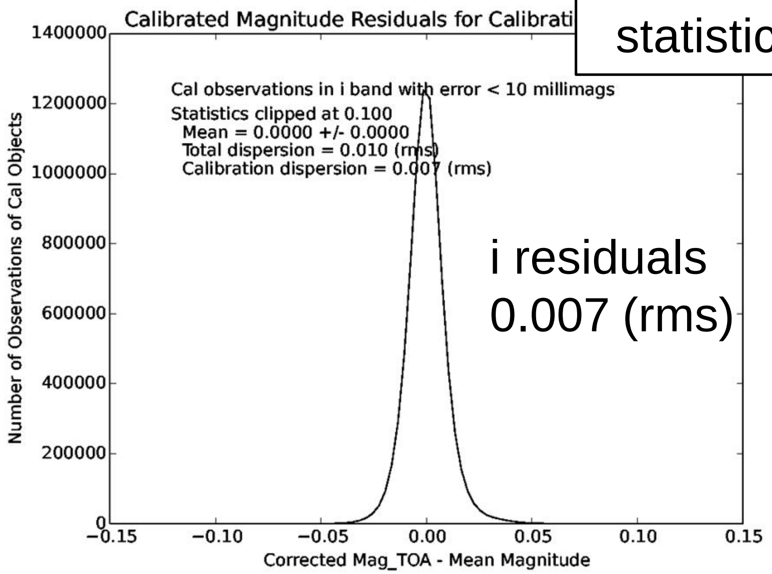


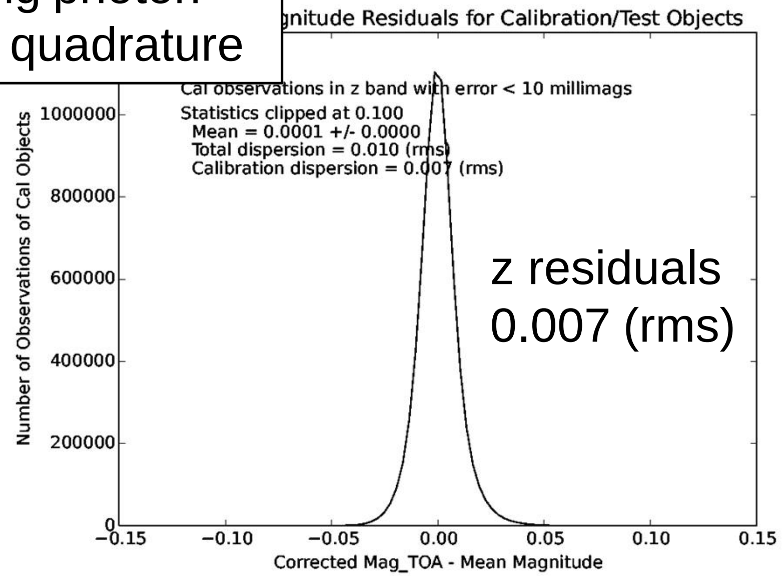
DARK ENERGY SURVEY



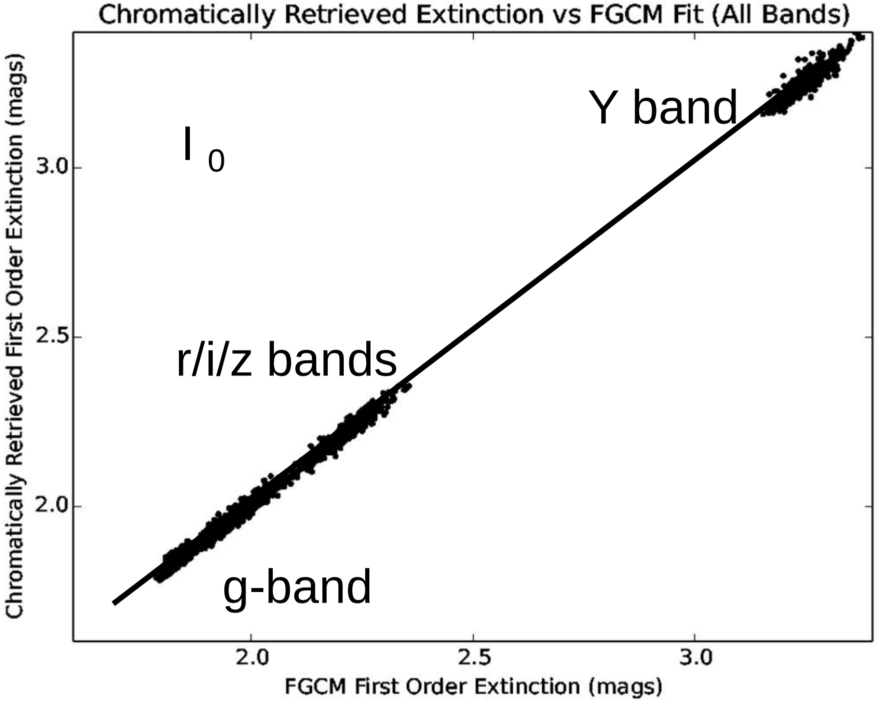


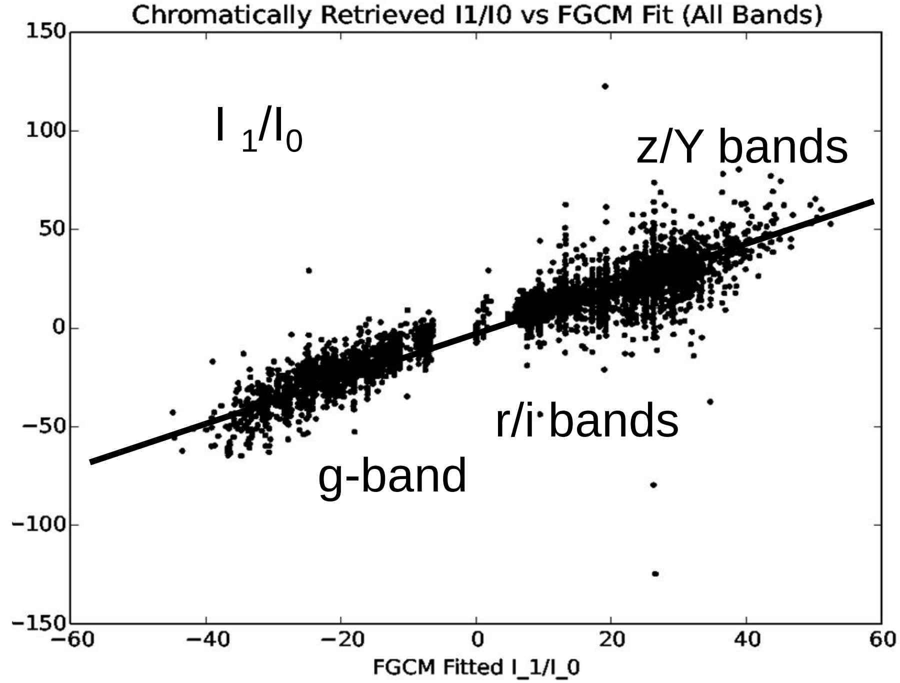
Residuals after subtracting photon statistics in quadrature

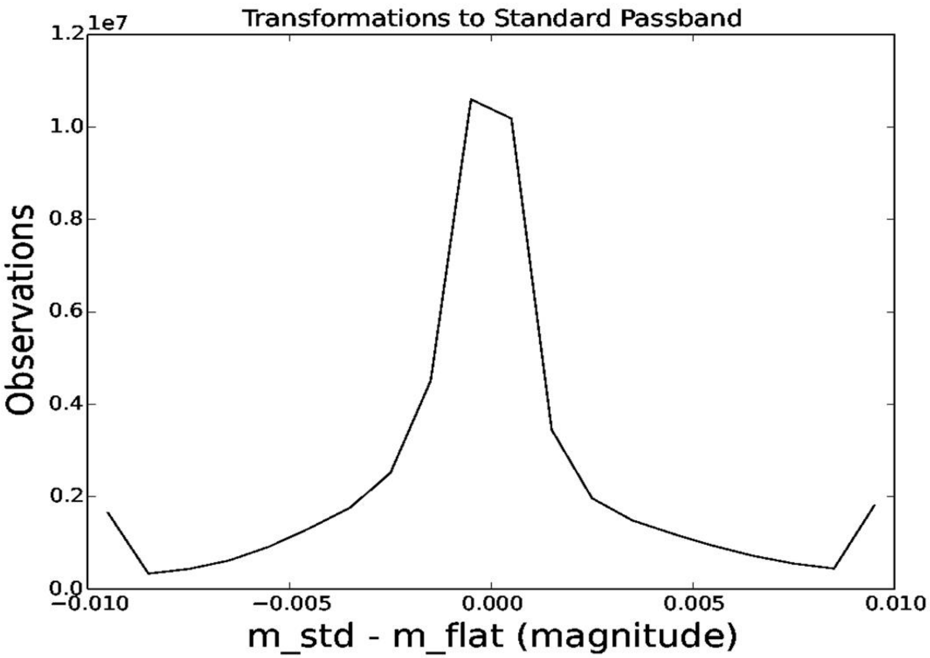




→ Standard magnitudes of MS stars with calibration precision ~ 7 mmag (rms)





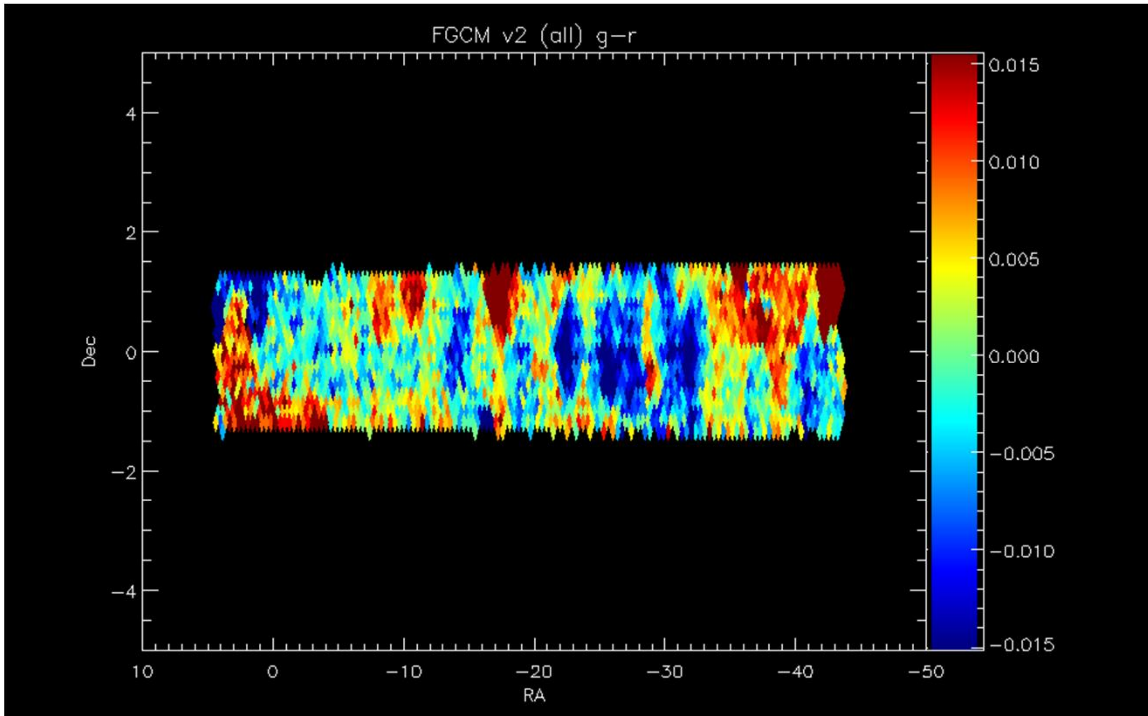


The Research Project

Retrieved values of I_0 and I_1/I_0 from fits to source spectral slopes (colors) and transformations to standard passbands

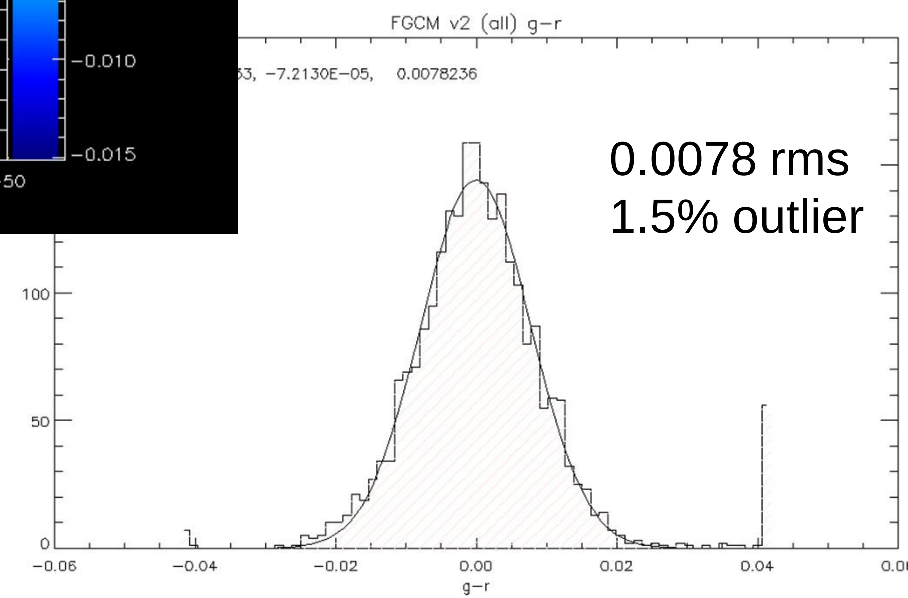
Comparison with CFHT at the TOA

Stripe 82 (Betoule 2013)



Semi-blind comparison:

DLB does calibration and E. Rykoff does SLR analysis and comparison with CFHT

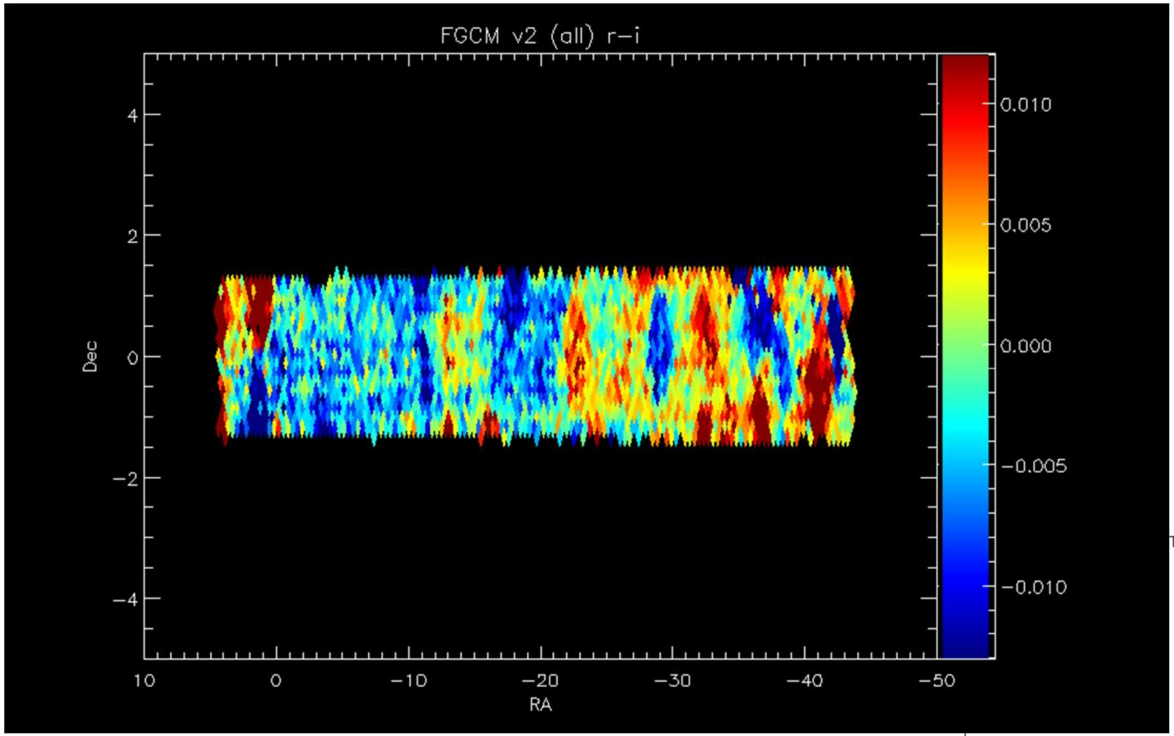


0.0078 rms
1.5% outlier

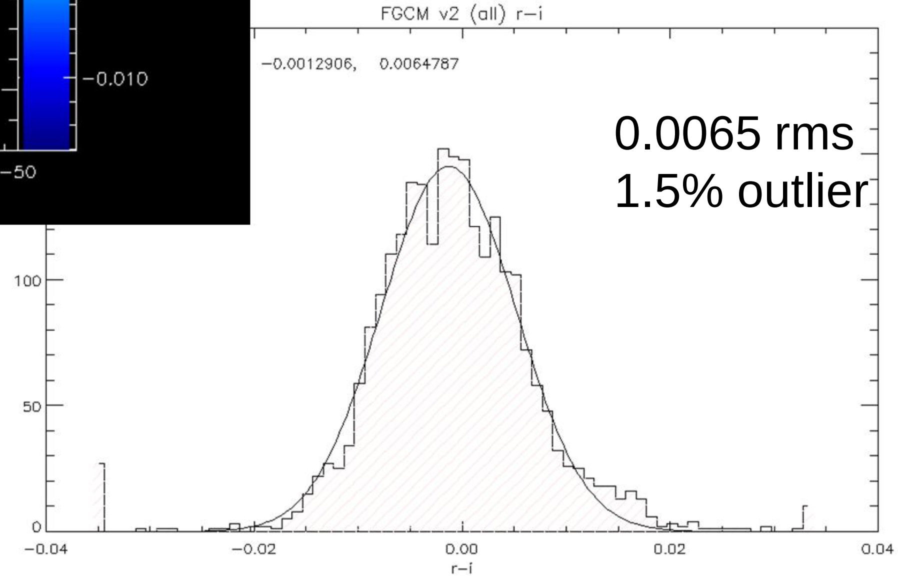
g-r color … after two-parameter fit to DES-CFHT passband transformations

Comparison with CFHT at the TOA

Stripe 82 (Betoule 2013)



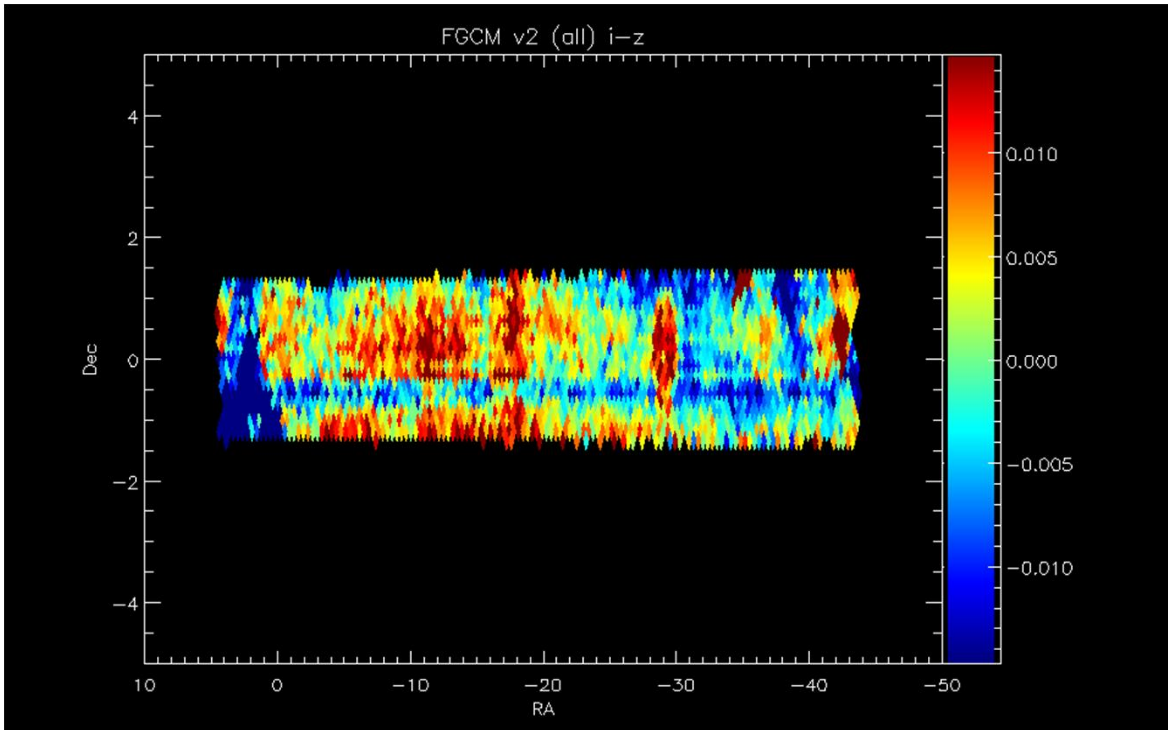
r-i comparison

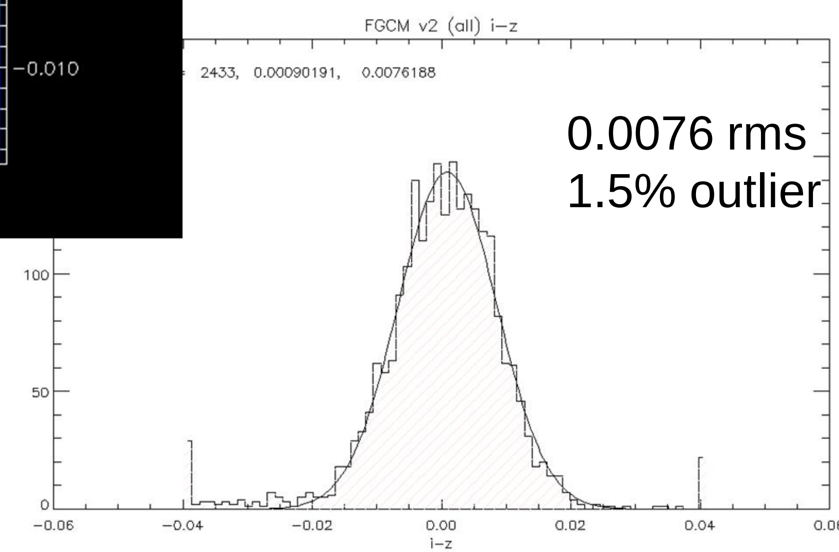


0.0065 rms
1.5% outlier

Comparison with CFHT at the TOA
Stripe 82 (Betoule 2013)

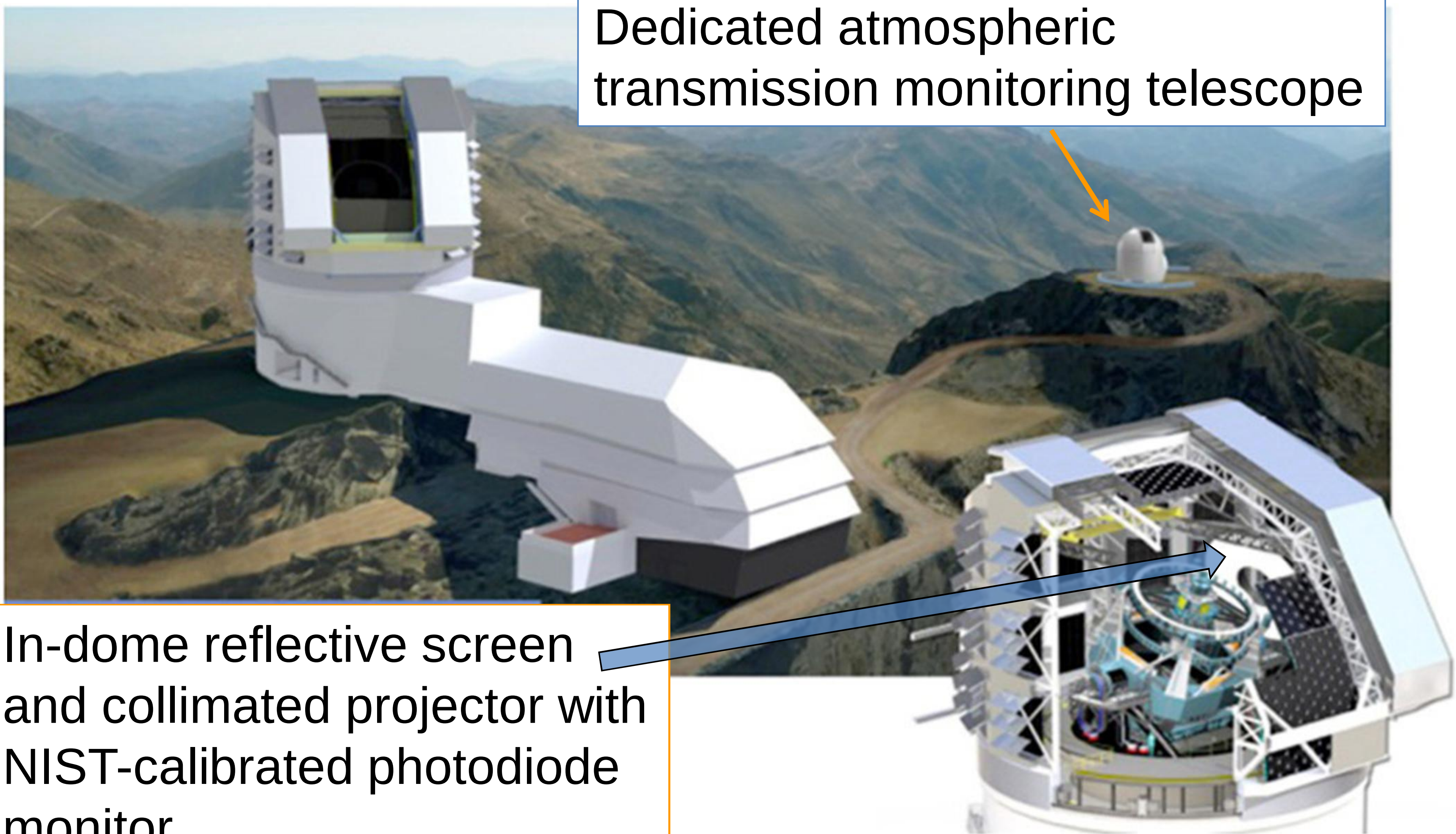
i-z comparison





Calibration Instrumentation for LSST

Dedicated atmospheric transmission monitoring telescope

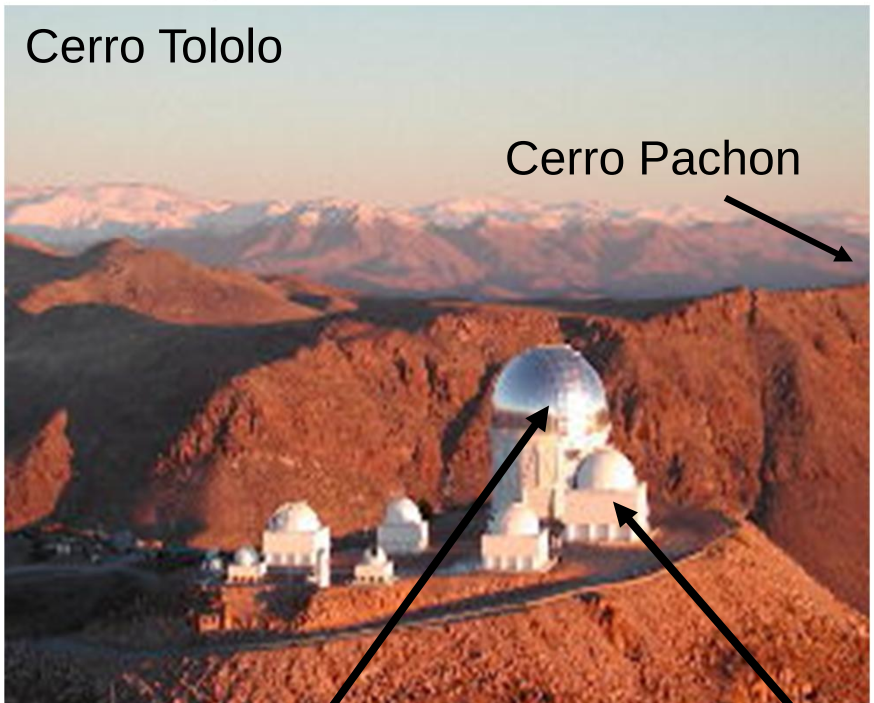


In-dome reflective screen and collimated projector with NIST-calibrated photodiode monitor

Observing Campaign at CTIO Tololo

NOAO Observing Proposal — *Standard proposal* — Panel: *For office use.*
Date: October 2, 2006 — Category: EGAL - Other

Characterizing Atmospheric Absorption for Precision Photometry



4m Blanco with MOSAIC II

1.5m Spectrograph

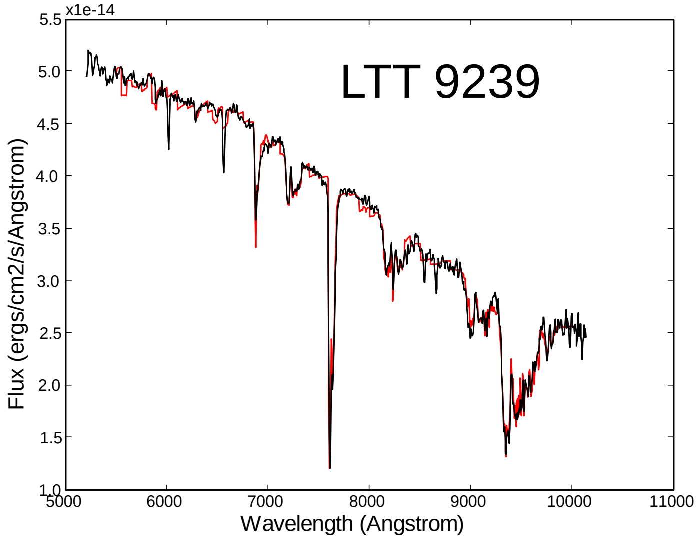
Five three-night observing runs in

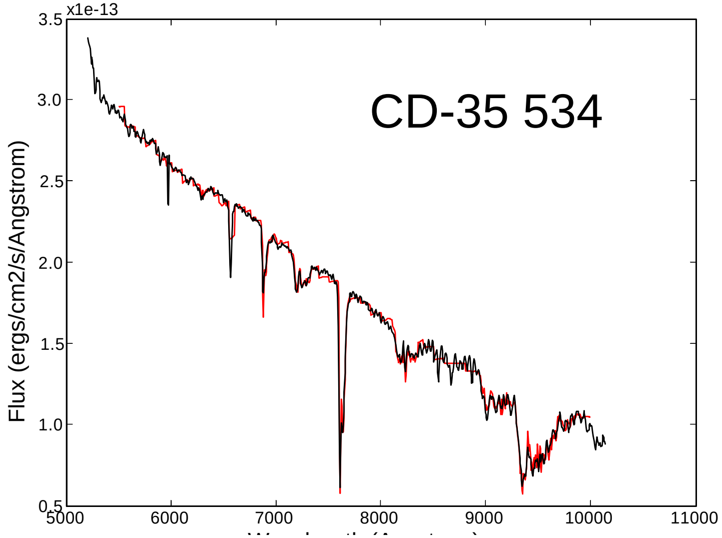
2007 April and November
2008 April and July
2009 July

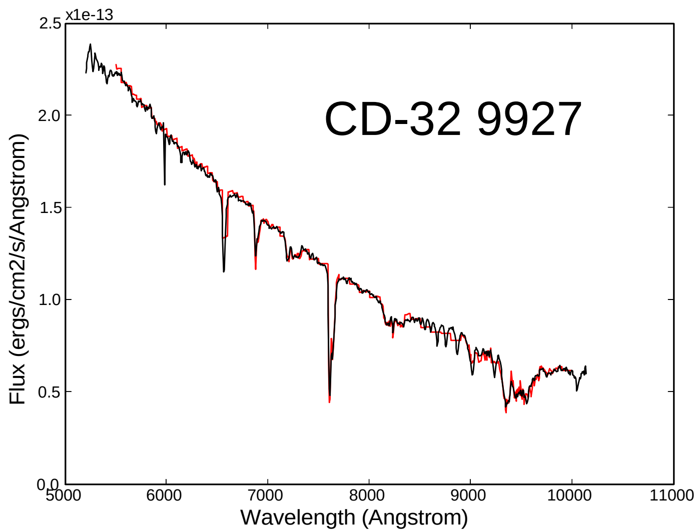
Goal to test atmospheric monitoring concept and develop practices

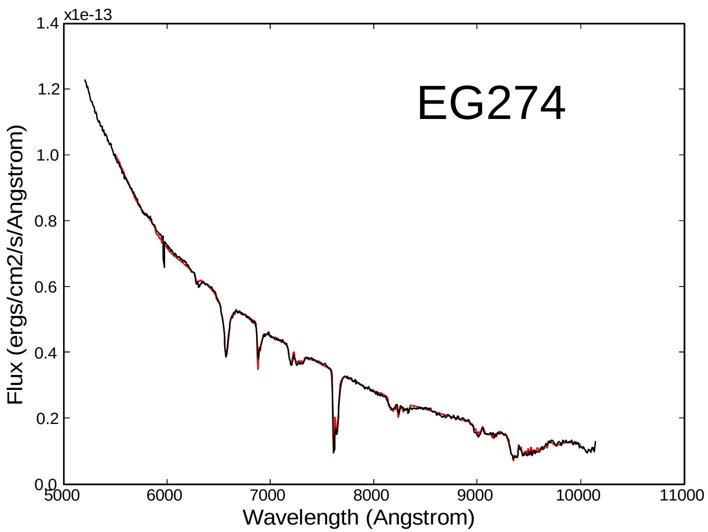
Example Fits

Spectra (Kurucz) and Atmosphere (MODTRAN)

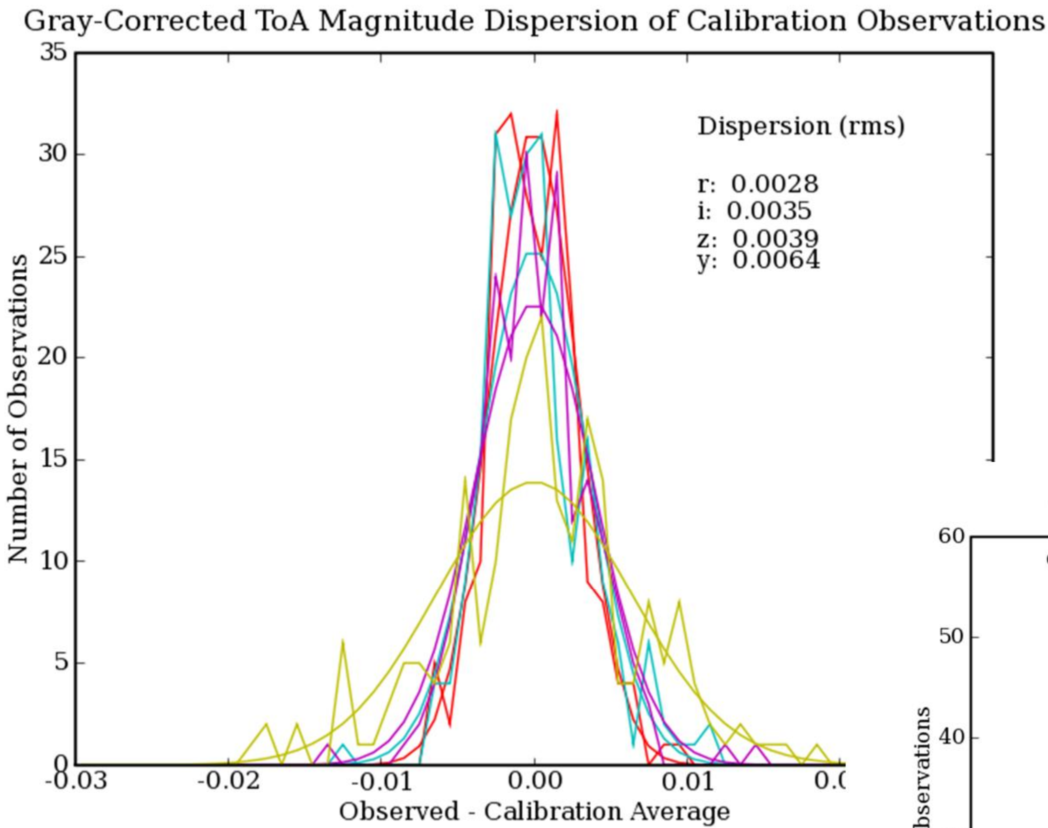






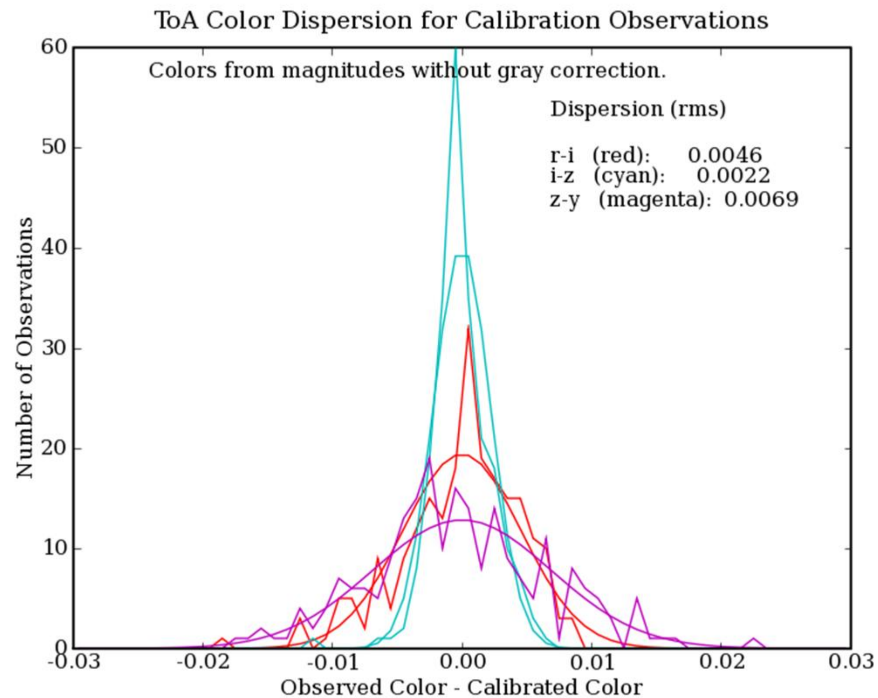


Bottom Line



Conclude that the technique accounts for all atmospheric components

Residual dispersion ~ 3 millimags in riz



Burke, et al., ApJ. 720, 811 (2010)

Done and Expected

Demonstrated feasibility of Forward Calibration concept and developed first-order chromatic paradigm suitable for production processing of DES and LSST data

Have 1% or better repeatability and uniformity in DES Year 1 data that covered half of the survey footprint

- Major limitation is number of repeated observations – significant fraction of the footprint observed only once or twice

Anticipate significant improvement with addition of aTmCam data starting in Year 2

- But observed alternate half of DES footprint, so sampling not likely to improve much

Anticipate continued improvement as Years 3-5 increase number of repeated observations of the full footprint